Technology Adoption and Environment: Theory and Evidence *
(preliminary draft)

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Abstract. The relationship between output and environmental quality improvement is studied in a vintage capital framework. In particular, we study how this relationship is altered when countries import older and more polluting technologies. We show that old technologies prolong the period until pollution may eventually decrease and this turning point is reached for a higher level of pollution. An empirical study on export data of vintage technologies to developing countries supports our empirical findings.
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1 Introduction

In the year 2002, the city of Dortmund, located in the western part of Germany, has been faced with one of the largest dismanteling operation ever.

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Over a thousand Chinese workers, accompanied by engineers started cut up into millions of pieces a huge iron and steel factory. About 250,000 tons of iron, steel, electrical devices, engines have been numbered, packed into boxes and sent 9000 kilometers further over the sea to China, where the factory, piece by piece, has been reassembled and is intended to produce about 5 million tons of steel yearly (Dohmen and Schmid, Der Spiegel, 2002).

Although markets for used machinery and equipment go back as far as the use of them, it is only in recent times that this market has really boomed, with double-digit growth rates and representing more then 150 billion euros per year (Janischewski, Henzler and Kahlenborn, 2003). A simple search on the Internet reveals the existence of dozens of auction houses, where sold objects go from simple tools to whole factories. On top of that, deals are often settled through Internet, facilitating thus transaction and promoting exchanges in second-hand goods.

The bulk of the flow of used machinery and equipment goes essentially from advanced to backward economies. Many less developed countries can thus access to means of production, despite stringent lack in capital, and have thus access to a low cost alternative to finance their economic growth. Besides the price argument, a popular argument in favour of used machinery good is the labour intensity explanation, which goes as follows: older technologies are more intensive in terms of labour to capital because they are less automated and because they often require more maintenance operations, which in turn are labour demanding. Coupled to the fact that absorptive capacities of new technologies depend on the skill availability of a country, developing countries are thus natural candidates for adopting these older types of technologies.

Recognizing this, it has been suggested to developing countries to reduce their barriers to trade on used machines and equipment (which are actually often more stringent than barriers on their new counterparts)[1] in order to facilitate their pace of development.

In the present study, we will not tackle the issue of lifting constraints on imports of used machinery and equipment in developing countries, but rather analyze how the use of old technologies influences the path of development of countries and how the shape of the output-pollution nexus is reshuffled when adopting older technologies rather then solely new ones.

The question raised by the transfer of vintage technologies to developing countries is whether these exports will promote (sustainable) development or not. Or, as put by Metz et al. (2005, p.15): "Economic development is most

[1] See for instance Czaga and Fliess (2005) and Navaretti et al (2000).

rapid in developing countries, but it will not be sustainable if these countries simply follow the historic greenhouse gas emission trends of developed countries. Development with modern knowledge offers many opportunities to avoid past unsustainable practices and move rapidly towards better technologies, techniques and associated institutions." In this context, one has probably to distinguish general durable second-hand goods, from equipment and machinery goods, in particular, energy intensive goods. Besides the fact that given the lifetime of this latter category of capital goods, this may exacerbate technological lag of LDCs (through later adoption of new technologies), environmental concerns may also be important given old technologies may be more environmental unfriendly. Thus, the induced advantage of low capital cost may be in the long term more then counterbalanced by higher energy costs and pollutant emissions (Janischewski, Henzler and Kahlenborn, 2003).

While carbon dioxide emissions have steadily increased in DCs during the last century, they have literally exploded in certain developing and transition nations such as China and India. By relying on thermal energy to support their growth, these countries will continue to increase their pollutant emissions. However, in order to support their development, more sustainable compatible means can be adopted, notably newer technologies that are less energy demanding. In this strand, the use of second-hand machinery and equipment plays a non-negligible role as older technologies are usually more environmental unfriendly and their adoption retards also the adoption of newer technologies.

Janischewski, Henzler and Kahlenborn (2003) provide several examples of environmental damages due to the use of older machinery and equipment. A 23 gigawatts fossil powerstation will cause about 2.2 billion tons of supplementary emissions of CO2 compared to modern power stations. Similarly, a fleet of 300,000 used cars will cause additional 6,000 tons of nitrogen oxide and 70,000 tons of carbon monoxide. Examples of this type abound.

This in turn, may induce important consequences on the output-pollution relationship. On the one hand, markets for used machinery and equipment may provide access to technologies in developing countries; but the use of these may retard the adoption of cleaner technologies, thus possibly reproducing in developing countries errors that developed countries have committed during their development process.

In the current paper we thus explicitly model how the decision to adopt older technologies affects the relationship between economic development and pollution. In order to do so we build on the Schumpeterian framework of Aghion and Howitt(1998) by introducing a vintage capital structure, where the law of motion of environmental quality will depend on the pollution flow and some upper limit on environmental quality that takes into account the exhaustibility of resources. We explicitly assume that new technologies are more environmentally friendly, enabling thus to shed light on the mechanisms through which the environmental quality affects growth performance following technological adoption.

Using our model we show that a reduction in environmental pollution during the industrialization process is only possible when the optimal rate of technological adoption has been reached. Moreover, the older the technology adopted, the later a hypothetical reduction of the pollution-output ratio will occur. However, even if the optimal rate of technological adoption has been reached, there is no guarantee that pollution decreases. Rather, we identify three possible outcomes concerning the relationship between pollution and economic development, where these depend on the rate of growth of investment relative to the rate of growth of environmental friendliness of technological improvement. First, there is the case that we term *weak sustainable development* where investment, consumption, and output increase at a constant rate, the level of pollution stabilizes, but environmental quality improves. Second an economy may achieve *strong sustainable development*, where investment, consumption, and output improve at a constant, but lower rate than under the former scenario, while pollution is decreasing. This latter case corresponds to the so-called Environmental Kuznets Curve, stating that countries start reducing their pollution per capita only after having reached a *sufficient* level of development. Finally, there may be the case where pollution increases unboundedly and environmental quality reaches its lower bound in finite time, which we refer to as the *catastrophic development*.

Our theoretical predictions have potentially important empirical implications. In particular, there is no guarantee that countries will ever decrease their pollution-output ratio. But even in the particular case they will, this turning point will be reached the later, the older the adopted technology. Using US and EU exports of used machinery and equipment to a set of developing countries, we show that countries importing relatively more vintage technologies tend also to reduce their pollution-output ratio for higher levels of output. Given that pollutants in general, and CO2 emissions in particular have very long standing effects, supporting the adoption of vintage technologies in developing countries today will have repercussions in the very long run. In this regard, the United Nations have realized the potential importance of this issue and supports now projects enabling the transfer of environmental sound technologies to developed countries.[2]

The rest of the paper is organized as follows: in section 2, we present a vintage capital model, where the planner sets the optimal age of the technology according to the stage of development. In section 3, using used goods exports from Europe and the US, we analyze the impact of these on the output-pollution relationship of a set of developing countries. Section 4 concludes.

2 A vintage capital structure

We consider a continuous time framework where the economy's population level is constant, and the labor market is perfectly competitive. The production sector produces only one final good, which can be assigned to consumption or net investment and plays the role of the numeraire. Moreover, we assume that in this economy there is no innovation. Technological change is due to adoption, which is costly. In the next section, we introduce the model, and present the explicit solution paths.

2.1 A general model

Production Sector As argued by Feichtinger et al. (2004) and Mulder et al. (2003) among others, there may be delays in the diffusion of new technologies. Arguably, developing countries may not access to the newest technology, either because of financial constraints or through lack of capacity to absorb the newest technologies. Therefore, supposing these countries have no innovation, we will assume that at time $t > 0$, not the newest technology is imported and adopted, but there is a delay period, which we denote by $0 < D < T(t)$, which can be interpreted as the exogenous youngest machine in use.[3] Following Boucekkine and Martinez (2003), per capita output $y(t)$ is assumed to be

$$y(t) = \int_{t-T(t)}^{t-D} i(z)dz. \tag{1}$$

where $0 < T(t) < \infty$ represents the vintage of the oldest machine in use (which is endogenously determined), and $i(z)$ is *gross* investment in a machine of age z, which includes the cost of adoption. In this case, $y(t)$ is in deed net output.

[2]See Metz et al. (2005) for a detailed account.

[3]If we set $D = 0$, our expression boils down to the traditional vintage capital model, where the new technology is instantaneously diffused (see Boucekkine et al., 1997).

Life expectancy of a machine is defined as $J(t) = T(t+J(t))$, i.e., the expected life of a machine at time t is equal to the scrapping time $T(\cdot)$, evaluated at $t + J(t)$, which corresponds to the time when this new machine will be scrapped in the future.

As can be seen from (1), we, in contrast to Stokey (1998), do not consider the level of pollution as an input in the production sector, but rather allow pollution to enter consumers' utility functions. This will allow us to draw conclusions on the perception of the trade off between consumption goods and environmental quality in developing *vs* developed economies.

Environment Sector As alluded above, in this economy, household agents care not only about their per capita consumption level $c(t) > 0$, but also pay attention to environmental quality. Following Aghion and Howitt (1998, Chap.5), we assume that there is an upper limit of to environmental quality, denoted by $\overline{E}$. We measure $E(t)$ as the difference between the actual quality and this upper limit. Thus, environmental quality will always be negative. The equation of motion of environmental quality is given by

$$\dot{E}(t) = -qE(t) - \int_{t-T(t)}^{t-D} i(z)e^{-\gamma z}dz, \tag{2}$$

where $\gamma > 0$ is the constant rate at which the pollution due to investment of vintage z declines, and $q > 0$ is the maximum potential rate of recovery of environment.[4] Pollution is measured by

$$P(t) = \int_{t-T(t)}^{t-D} i(z)e^{-\gamma z}dz. \tag{3}$$

One should note that from (2) pollution is a side-product of investment $i(z)$ in the production sector. Implicit in (2) is the assumption that new machines are less polluting than older ones. Using a newer vintage leads henceforth to reduced pollution per input. Note finally that pollution is the opposite of environmental quality, up to the first term on the RHS of expression (2) denoting the self-regeneration capacity of nature.

Per capita output $y(t)$ can be consumed, $c(t)$, or invested in a vintage capital good, $i(t) \geq 0$,

$$y(t) = c(t) + i(t). \tag{4}$$

[4] The notion of sustainable development is intimately linked to the one of self-regeneration capacity, as noted by the World Bank (1991a and 1991b).

Central Planner The central planner's objective function will entail per capita consumption and environmental quality. More particularly, the planner will choose the paths of consumption and environmental quality in order to maximize the instantaneous utility of the infinitely lived representative household,

$$\max_c \int_0^\infty U(c, E)\, e^{-\rho t} dt = \max_c \int_0^\infty [\beta c(t) - (1-\beta)E(t)] e^{-\rho t} dt, \tag{5}$$

subject to (2), (4), and

$$J(t) = T(t + J(t)), \tag{6}$$

where $\rho > 0$ is the constant time preference, $0 < \beta \leq 1$ is a weight parameter between consumption goods and environmental quality, and $i(z)$, $z \leq 0$ and $E(0)$ are given functions. Furthermore we assume that $0 < \gamma < \rho < 1$, which are necessary and sufficient conditions for the existence of a balanced growth path in an exogenous growth models.[5]

2.2 Optimal solution Path

After rearranging the terms and changing the order of integrals, the optimal control problem can be represented as looking for $i(t)$, $J(t)$, with the state variable $E(t)$, as is shown in the Appendix.

First order condition with respect to $E(t)$ lead to

$$\begin{cases} \dot{\mu}(t) = (\rho + q)\mu(t) + (1 - \beta), \\ \lim\limits_{t\to\infty} E(t)\mu(t)e^{\rho t} = 0. \end{cases} \tag{7}$$

Expressions (7) combined with the transversality condition provide Tobin's q in the sense of environmental quality, which is the shadow value of environmental quality. As in the optimal investment profile, this shadow value determines the optimal scrapping rule (8), and the optimal investment strategy (9) here below.

First order condition with respect to $J(t)$ provides

$$\mu(t) = \beta e^{\gamma(t - T(t))}. \tag{8}$$

[5] In order to obtain explicit solutions, we avoid more general utility functions. While general utility functions would allow us to write down optimal conditions as in Ramsey type models, the equilibrium conditions for such an economy would give rise to a mixed-delay differential equation system with endogenous leads and lags (see Boucekkine et al., 1997).

The optimal scrapping rule (8) means that a machine should be scrapped as soon as its operation cost with respect to consumption no longer covers its market value in terms of environmental quality.

First order condition with respect to $i(t)$ provides

$$\beta \int_{t+D}^{t+J(t)} e^{-\rho z} dz - \beta e^{-\rho t} = \int_{t+D}^{t+J(t)} e^{-\rho z} \mu(z) e^{-\gamma t} dz, \tag{9}$$

which states that the optimal investment strategy should be such that at time t the discounted marginal productivity during the whole lifetime of the capital acquired in t exactly compensates for both its discounted operation cost and its discounted environmental shadow value, where the first term on the LHS is the discounted marginal productivity during the whole lifetime of the capital acquired at time t, and the second term is the marginal purchase cost at t normalized to one. The RHS expression is the discounted environmental shadow value at time t.

In the next section, we study the dynamics of $T(t)$, since the block recursive structure of our problem allows us to obtain explicitly $T(t)$, $J(t)$, and $\mu(t)$ by solving (9), (8) and (7). In doing so, we first assume that there exists a t^*, such that, $0 \leq t^* < \infty$, and when $t > t^*$, the interior solution is obtained, and provides the optimal scrapping rule. Then, through the dynamics of $T(t)$, we prove the existence of t^*.

2.3 Optimal scrapping rule

As is standard in the vintage capital literature, we first solve the timing of both $T(t)$ and $J(t)$.

Substituting (8) into (9), it follows

$$\frac{1}{\rho}\left(e^{-\rho D} - e^{-\rho J(t)}\right) - 1 = e^{(\rho-\gamma)t} \int_{t+D}^{t+J(t)} e^{-\rho z} e^{\gamma(z-T(z))} dz. \tag{10}$$

Deriving expression (10) with respect to time and rearranging the terms, we obtain the optimal scrapping rule

$$T(t+D) = F(J(t)) = -\frac{D}{\gamma}(\rho-\gamma) - \frac{1}{\gamma} \ln\left(\left(1-\frac{\gamma}{\rho}\right) e^{-\rho D} - (\rho-\gamma) + \frac{\gamma}{\rho} e^{-\rho J(t)}\right), \tag{11}$$

which, gives the expected life time of the youngest machines in use.

Function $F(\cdot) : \mathbb{R}_+ \to \mathbb{R}_+$ is well defined if and only if the following conditions hold.

Assumption 1. The parameters and exogenous variables must check the following conditions:

$$0 < \gamma < \rho < 1,$$
$$\rho e^{\rho D} < 1.$$

Proposition 1 *(Proof: see Boucekkine et al. (1997)). Let Assumption 1 hold. Then for $t > t^*$, the unique differential interior solutions of $T(t)$ and $J(t)$ are given by*

$$J(t) = T(t+D) = T^* = -\frac{D}{\gamma}(\rho-\gamma) - \frac{1}{\gamma}\ln\left(\left(1-\frac{\gamma}{\rho}\right)e^{-\rho D} - (\rho-\gamma) + \frac{\gamma}{\rho}e^{-\rho T^*}\right),$$

where T^* is the positive fixed-point of function $F(\cdot)$, and t^* will be given in proposition 3. Furthermore, the optimal scrapping age T^* is increasing with D (see appendix).

The optimal scrapping age does not depend on the weight between consumption goods and environmental quality. However, it depends on consumers' time preference and on the technology program. Thus, different economies may highlight different optimal paths!

The intuition of the increasing effect of D on T^* is straightforward. Given T^* is the optimal age at which a machine has to be scrapped, if $D = 0$, i.e., the newest technology is adopted, then T^* is the period during which this technology will be in use. However, if $D > 0$, then T^* will be the period during which the technology will be used *and* the age of the technology when it was originally adopted. In other words, when an economy adopts an older technology, the total age of this technology will be higher compared to the case where an economy adopts a new technology.

2.4 Transition dynamics

In the appendix we prove the following results.

Proposition 2 *During the transition dynamics, the scrapping rule is given by*

$$T(t) = t - \frac{\rho+q}{\gamma}t - \frac{1}{\gamma}\ln\left(e^{-\gamma T(0)} + \frac{1-\beta}{\beta(\rho+q)}\left(1-e^{-(\rho+q)t}\right)\right), \qquad (12)$$

which is independent of D, but decreasing with respect to t, and increasing with respect to $T(0)$.

During the transition, whatever the vintage of the adopted technology, it will have no impact on the scrapping rule. [Why? Blablabla]

A straight forward consequence of the above proposition is the following.

Proposition 3 *Given an investment profile of a country, if initially $T(0) < T^*$, then this economy should instantaneously jump to the optimal scrapping path. In this case, $t^* = 0$. Conversely, if $T(0) > T^*$, there exists a time t^0, such that, $0 < t^0 < \infty$, in which case $t^* = t_0$.*

Intuitively, since the endogenous scrapping time $T(t)$ is increasing with the initial scrapping time $T(0)$, if an economy starts with a relatively high stock of machines, and scraps too fast, it is impossible, for any positive t, that $T(t)$ reaches T^*, the optimal path, given the endogenous scrapping program is decreasing with time. Henceforth, the only way to reach the optimal path is to immediately jump to this optimal path. Aghion and Howitt (1998, Chap.5) have developed this idea under a Schumpeterian framework. However, they only show that there is some initial value of capital for this to happen, while we provide the explicit conditions under which this jump could indeed occur.

For the developing economy case, the instantaneous jump to the optimal path could be impossible (even though starting from a corner solution, that is, zero consumption and all output invested in physical capital). Instead of an immediate technology adoption, which would compensate the initial low level of vintage physical capital, there are time delays of adoption, given new technologies are too costly. Thus, for relatively poor economies, older and relatively environmental unfriendly machines will be employed for a certain period, until the optimal path is reached.

As mentioned in the previous analysis, when $T(0) > T^*$, the economy starts with a relatively low stock of capital. Then in order to reach the interior solution (and thus, the optimal path, if there is one) as fast as possible, one possibility is to invest all output. In this case, starting from a corner solution, the economy subsequently produces and pollutes

$$y(t) = \int_{t-T(t)}^{t-D} y(z)dz, \quad P(t) = \int_{t-T(t)}^{t-D} y(z)e^{-\gamma z}dz, \tag{13}$$

when $0 < t < t^*$. Indeed, pollution increases with the accumulation of output $y(\cdot)$, during all the periods the machine is in use. Moreover, there is also a *delay effect* on pollution coming from output.

Proposition 4 *The following comparative result can be obtained (see appendix)*

1. $\frac{\partial(y(t;D))}{\partial D} < 0$, $\frac{\partial(P(t;D))}{\partial D} < 0$. *Increasing the age of the youngest machines employed will decrease the output and the pollution level.*

The first results simply states that older machines will be used a shorter period. The second effect, i.e., older machines reduce pollution, follows immediately from the former one. Given pollution results straightforwardly from investment, if output (which is measured as the accumulation of investment) decreases, pollution will do so as well.

2.5 Optimal scrapping age

In this subsection, we assume that after reaching the optimal scrapping age $T(t) = T^*(D)$, for all $t > t^*$, the economy will still use machines of age D as their youngest machines in use. However, consumption will no longer be zero, and all output will be used for investment and consumption.

Furthermore, considering a special case where investment follows an exponential rule, that is $i(t) = i^* e^{gt}$, where $i^* > 0$ is the investment level and $0 \leq g < 1$ is the growth rate of investment. From the market clearing condition (4), it is trivial to see that output and consumption follow the same growth rate as investment. Therefore, we have that $y(t) = y^* \cdot e^{gt}$ and $c(t) = c^* \cdot e^{gt}$, for all $t > t^*$. In order to guarantee non-zero consumption, the following condition is sufficient.

Assumption 2. $0 < \gamma < \frac{\rho}{2}$.

We obtain the same conditions and results as in Bertinelli et al. (2005).

Proposition 5 *Suppose Assumptions 1 and 2 hold. Let $t > t^*$. (a) There is a BGP, where investment, consumption, and output grow at constant rate γ, the growth rate of environmental quality is $q > 0$, and pollution levels are stable. Furthermore, sustainable growth is guaranteed and environmental quality will permanently improve, though never reach its upper bound. (b) When $g > \gamma$, there is no BGP and the economy converges towards the catastrophic outcome in finite time. We refer to this case as the over-investment case. (c) If $g < \gamma$, output, investment, and consumption grow at rate g, where g will be either $0 < g < \min\{\gamma, 1 - e^{-gT^*}\}$, or $g = 0$. In this case, environmental quality will constantly improve and tend to the upper bound* *in the long run, but not at a constant rate of growth. Pollution is always decreasing at rate $\gamma - g$. We call this case the under-investment case.*

Furthermore:

(I) If the BGP is reached, pollution is independent of output and time, and only depends on the optimal scrapping age and the turning point of investment in the economy;

(II) If we are in the under-investment case, then pollution is decreasing with time;

(III) If we are in the over-investment case, pollution will be increasing over time

In the following, we are going to compare the effect of D on the EKC.

If one is along the balanced growth path, i.e., the growth rate of investment is the same as the rate at which environmental friendliness of technology (γ) improves, it follows

$$y(t) = \frac{i^* e^{\gamma t}}{\gamma}(e^{-\gamma D} - e^{-\gamma T^*}), \quad P(t) = i^*(T^* - D).$$

In this case, pollution is independent of output and time, but output is increasing with time t. The pollution/output ratio is then given by

$$\frac{P(t)}{y(t)} = \gamma \frac{T^* - D}{e^{-\gamma D} - e^{-\gamma T^*}} e^{-\gamma t},$$

which is decreasing with time t and converges to 0.

It follows

$$\frac{\partial \left(\frac{P(t)}{y(t)}\right)}{\partial D}$$

3 Empirical analysis

Our theoretical model has provided arguments supporting the idea of delays in the timing when countries could potentially reduce their pollution-output ratio if older rather than new technologies are adopted. In the sequeal, we are going to investigate this issue empirically. Special emphasis will be devoted to the non-linearity of the output pollution relationship and how this relationship depends crucially on the share of imported used machinery and equipment.

3.1 Data

In order to investigate the ouput pollution relationship, we, as is standard in these types of studies, will have recourse to a measure of carbon dioxide emissions to proxy pollutants. Emissions of carbon dioxide result from the combustion of organic matter. As such, potentially any activity involving combustion created carbon dioxide, although non-fossil fuel energy tend to release less carbon than fossil fuel. Data used in this study rely on energy statistics from almost only on fossil fuels, leaving aside emissions of carbon dioxide resulting from cumbustion of non-fossil fuel, such as wood, waste, etc. Despite its potential importance, most of the non-fossil fuel energy use cannot be included in this study due to the lack of reliable data. One has however to note that since at least the early 19th century, *fossil fuels* have been critical to economic growth, and have also been recognized as major contributers to environmental degradation, by generating greenhouse gazes.[6] Focusing our attention on carbon dioxide emissions solely is less restrictive than it may appear in first instance.

In this regard we use data on carbon dioxide from the Carbon Dioxide Information Analysis Center compiled by Marland et al. (2003), where the earliest available data goes as far back as 1751, and extends up until 2000. The data represents total national carbon dioxide emissions from fossil-fuel burning, cement manufacture, and gas flaring, and is expressed in thousands of metric tons. In order to get per capita figures, carbon dioxide emissions have been divided through by population data.

Our second variable is the measure of output, which we proxy by GDP per capita. Data stems from Maddison (2001, 2003). These measures are appropriatly adjusted for purchasing power parity (and expressed in million 1990 International Geary-Khamis dollars).

The last variable of interest, which allows us to distinguish the adoption of new and used technology is the import of used machinery and equipment from the EU and the US. In particular, we used trade data from the Eurostat Comext database for European exports and from USA Trade Online for US exports. Detailed information about the sectors that have been considered are provided in the appendix. Trade flows were available at current values. Given we are interested in *shares* of used goods, we did not have to deflate these measures. In order to get a measure of the importance of used goods imports in our set of developing countries, we have computed the share of ag-

[6] Besides carbon dioxide, methane and nitrous oxide are the other two important greenhouse effect gazes.

gregated used to aggregated total imports of machinery and equipment, and used the resulting measure to proxy the importance of vintage technologies in every country under scrutiny.

In terms of periods under scrutiny, whereas 200 years were available for carbon dioxide and about 50 years for GDP and openness, we had to restrict our study from the late 1980s up to 2000 given data availability for the trade flows. In particular, we have 11 years of observations for trade flows from Europe (1988-1998) and 9 years for US data (1992-2000).

Finally, we have around 100 developing countries for which we have information about pollutants, GDP/capita and trade. A complete country list is available in the appendix.

[Table: descriptive statistics]

3.2 Estimation

Our theoretical model has shown that the pollution-output relationship is modified when countries use older technologies. In particular, we have shown that if the steady state is reached the pollution-output ratio decreases for higher levels of output when countries use older technologies. In other words, one may expect that developing countries importing *high* levels of vintage technologies, will have high pollution per output ratios that will persist for longer time. Moreover, if there is a turning point, i.e. if the pollution-output relationship is bellshaped as suggested by the proponents of the Environmental Kuznets Curve (EKC), then our model predicts that this turning point will happen for a higher output level.

In order to assess these predictions, we have pooled our cross-country data for the period 1992 to 1998, for which we had data on all our variables of interest. Table 1 presents results for a standard EKC specification

$$\begin{aligned} CO2/capita &= \alpha + GDP/capita\,(\theta_0 + \theta_1 \cdot GDP/capita) \\ &\quad +R\delta + T\lambda + \epsilon \end{aligned} \tag{14}$$

where θ_0 and θ_1 account for the (possibly non-linear) impact of GDP per capita on carbon dioxide emissions, and the coefficients δ and λ in the second line capture the time invariant regional effects and the country invariant time effects respectively. Last, ϵ is the error term, supposed to be *iid*.

As expected, in column 1, the positive and highly significant coefficient of per capita GDP (θ_0) points towards an increasing effect of output on pollution. This comes as no surprise, since it is well known that our measure of pollutant, namely carbon dioxide, crucially depends on energy consumption, which in turn is a major input in production. This result holds even after controlling for time-invariant regional fixed effects and time dummies, in column 3.

Our theorectical model has shown that under some parameter conditions, we may end up with a decreasing pollution-output curve, when countries have reached a *high enough* level of development. This comes as an echo to the seminal paper by Grossman and Kruger (1991), where these authors showed that the link between per capita GDP and pollution follows an inverted U-shaped pattern. In columns 2 and 4, we take account for this possible non-linearity by introducing GDP per capita as a polynomial of order two in our estimated specification

In both cases, i.e. when taking account or not of time and regional dummies, our specification supports the existence of an inverted U-shaped relationship. This finding could suggest that lower income regions are 'too poor to be green', and only when these become rich enough will the benefits from a clean environment outweigh its costs. One has however to note that the maximum of this curve would only be reached for values of GDP per capita that by far exceed the richest country's maximum value, making thus an inverted U-shaped relationship quite hypothetical.

In Table 2, we have added our variable of main concern, namely share of used imported goods. As suggested by our theoretical model, this variable has the effect of retarding a deceleration respectively a decrease in pollution. In order to test for this result, we have reestimated the same specifications as in Table 1 by adding an interaction term of share of used goods with GDP per capita and its square

$$+\,(Share\ used\ goods)\cdot\ [\beta_0 + \beta_1 \cdot GDP/capita \qquad (15)$$

$$+\beta_2 \cdot (GDP/capita)^2] \qquad (16)$$

Results from columns 1 as well as 3 (which coorespond to specification (14), where (15) has been added) support the somehow intuitive argument that countries importing older technologies have a tendency to pollute more, i.e. the slope coefficient of GDP per capita is an increasing function of the share of used goods. To get a sense of this, a one standard deviation increase of GDP per capita in our sample will increase pollution by 0.358 tons per inhabitants per year if the country imports only new equipment goods, but 0.520 tons per person in case the country's imports of equipment goods are equally split between used and new goods. For comparison, average carbon dioxide consumption in 1998 for the countries in our sample was 0.526!

In columns 2 and 4, we have again accounted for possible non-linearities in the pollution-output relationship. More specifically, we have added (15) and (16) to specification (14). In both specifications (i.e. with and without time and regional dummies), the impact of the share of used goods on carbon dioxide is first decreasing and then increasing with per capita GDP. However, β_1 is only significant at 21 per cent respectively 14 per cent for columns 2 and 4. Thus columns 1 to 4 of Table 2 point towards an increasing relationship between pollution and output, and moreover, the higher the share of imported used goods, the steeper the slope of this relationship.

In Figure 1, we have represented the results of column 2 and 4 of Table 2, where α, θ_0, β_0, δ and λ have been normalized to 0. The three curves represent parameter values of share of used goods of 10, 50, and 90 per cent respectively. As it appears clearly on both figures, the outcome on the pollution output relationship differs widely according to the type of technology that is imported. Whereas low shares of imported used goods are consistent with the standard EKC result, i.e. an inverted U-shaped relationship between pollution and output, the same is not true for higher values of our variable of interest. When setting the share of used goods at 50 per cent, the relationship is still an inverted U shaped, but the maximum would be reached for a hypothetical GDP per capita value of 49423\$,[7] which is about 2.5 times the maximum value in our sample! This means that the pollution output relationship is essentially always increasing for feasible values of GDP per capita, but at a decreasing rate. Last, when we set the share of used imported goods to 90 per cent, the relationship becomes convex, i.e. an increase in output per capita induces a more than proportional increase in pollution.[8]

4 Conclusion

TBD

[7] This maximum value was 12308\$ when the share value was set to 10 per cent.

[8] The value for which the relationship becomes convex is actually 63.3 per cent.

5 Appendix

5.1 Optimal control problem is section 2.2

The market clearing condition (4) can be denoted

$$\begin{aligned}\mathcal{L}(i(t),T(t),E(t)) &= \int_0^\infty e^{-\rho t}\left[\beta\left((1-\alpha)\int_{t-T(t)}^{t-D} i(z)dz - i(t)\right) - (1-\beta)E(t)\right]dt \\ &- \int_0^\infty e^{-\rho t}\mu(t)\left[\dot{E}(t) + qE(t) + \int_{t-T(t)}^{t-D} i(z)e^{-\gamma z}dz\right]dt.\end{aligned}$$

Integrating by parts and changing the order of the integrals, it follows

$$\begin{aligned}\mathcal{L} &= \int_0^\infty\int_{t+D}^{t+J(t)} \beta(1-\alpha)i(t)e^{-\rho z}dzdt - \int_0^\infty \beta e^{-\rho t}i(t)dt \\ &+ \int_0^\infty (\dot{\mu}(t) - \rho\mu - q\mu - (1-\beta))E(t)e^{-\rho t}dt \\ &- \int_0^\infty\int_{t+D}^{t+J(t)} i(t)e^{-\gamma t}\mu(z)e^{-\rho z}dzdt + E(0)\mu(0) \\ &+ \int_{-T(0)}^{-D}\int_0^{t+D)} i(t)e^{-\gamma t}\mu(z)e^{-\rho z}dzdt \\ &+ \int_{-T(0)}^{0}\int_{t+D}^{t+J(t)} i(t)e^{-\gamma t}\mu(z)e^{-\rho z}dzdt \\ &+ \int_{-T(0)}^{-D}\int_0^{t+D)} \beta(1-\alpha)i(t)e^{-\rho z}dzdt + \int_{-T(0)}^{0}\int_{t+D}^{t+J(t)} \beta(1-\alpha)i(t)e^{-\rho z}dzdt.\end{aligned}$$

Notice that before $t=0$, all the endogenous variables are given, so the last 4 terms in $\mathcal{L}$ will have no effect on the first order conditions, except if we provide the initial conditions.

The first order conditions with respect to the control variables $i(t)$, $J(t)$, and the state variable $E(t)$ will be:

$$\frac{\partial\mathcal{L}}{\partial i(t)} = 0, \quad \frac{\partial\mathcal{L}}{\partial J(t)} = 0, \quad \frac{\partial\mathcal{L}}{\partial E(t)} = 0.$$

5.2 Proof of Proposition 1

Let $t > t^*$. After changing forms, (11) can be rewritten as

$$e^{-\gamma T^*} = e^{(\rho-\gamma)D}\left[\frac{\rho-\gamma}{\rho}e^{-\rho D} - (\rho-\gamma) + \frac{\gamma}{\rho}e^{-\rho T^*}\right], \tag{17}$$

and denote

$$A = \left[\frac{\rho-\gamma}{\rho}e^{-\rho D} - (\rho-\gamma) + \frac{\gamma}{\rho}e^{-\rho T^*}\right].$$

The derivative of equation (17) with respective to D shows that

$$\frac{\partial T^*}{\partial D} = -\frac{\rho-\gamma}{\gamma}\frac{\left(A - e^{-\rho D}\right)}{\left(A - e^{-\rho T^*}\right)}.$$

Hence the effect of D on T^* will depend on the signs of $\left(A - e^{-\rho D}\right)$ and $\left(A - e^{-\rho T^*}\right)$.

We can easily prove that

$$A - e^{-\rho D} = \frac{\gamma}{\rho}\left(e^{-\rho T^*} - e^{-rhoD}\right) - \frac{\rho-\gamma}{1-\alpha} < 0.$$

Then the effect will depend on $\left(A - e^{-\rho T^*}\right)$ only, and $A - e^{-\rho T^*} > 0$ is equivalent to

$$T^* > \tilde{T}^* \equiv -\frac{1}{\rho}\ln\left(e^{-\rho D} - \rho\right).$$

In the following, we are going to prove that this statement is always true. Hence $A - e^{-\rho T^*} > 0$ is always true.

>From the from of T^* given in the first part of Proposition 1, we have that

$$\begin{aligned}
T^* &= -\frac{D}{\gamma}(\rho-\gamma) - \frac{1}{\gamma}\ln\left(\left(1-\frac{\gamma}{\rho}\right)\left(e^{-\rho D}-\rho\right) + \frac{\gamma}{\rho}e^{-\rho T^*}\right) \\
&> -\frac{D}{\gamma}(\rho-\gamma) + \frac{\rho}{\gamma}\left(-\frac{1}{\rho}\right)\ln\left(\left(1-\frac{\gamma}{\rho}\right)\left(e^{-\rho D}-\rho\right)\right) \\
&> -\frac{D}{\gamma}(\rho-\gamma) + \frac{\rho}{\gamma}\left(-\frac{1}{\rho}\right)\ln\left(\left(e^{-\rho D}-\rho\right)\right) \\
&= -\frac{D}{\gamma}(\rho-\gamma) + \frac{\rho}{\gamma}\tilde{T}^*,
\end{aligned}$$

where the inequalities come from the fact that the logarithmic function is increasing. From these inequalities, we straightforwardly obtain

$$\begin{aligned} T^* - \tilde{T}^* &> -\frac{D}{\gamma}(\rho - \gamma) + \frac{\rho}{\gamma}\tilde{T}^* - \tilde{T}^* \\ &= \frac{\rho - \gamma}{\gamma}(\tilde{T}^* - D) \\ &> 0. \end{aligned}$$

Combining the above analysis, we have that T^* is increasing with D.

5.3 Proof of Proposition 2

From (8), we have that $\mu(0) = \beta e^{-\gamma T(0)}$. Hence it is easy to get

$$l\mu(t) = e^{(\rho+q)t}\left[\beta e^{-\gamma T(0)} + \frac{1-\beta}{\rho+q}\left(1 - e^{-(\rho+q)t}\right)\right].$$

Combing $\mu(t)$ with (8), we have

$$e^{-\gamma T(t)} = e^{(\rho+q-\gamma)t}\left[e^{-\gamma T(0)} + \frac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)\right].$$

Hence,

$$T(t) = T(t;T(0)) = t - \frac{\rho+q}{\gamma}t - \frac{1}{\gamma}\ln\left(e^{-\gamma T(0)} + \frac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)\right).$$

Furthermore,

$$\frac{\partial T(t;T(0))}{\partial T(0)} = \frac{e^{-\gamma T(0)}}{e^{-\gamma T(0)} + \frac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)} > 0,$$

and

$$T'(t) = 1 - \frac{\rho+q}{\gamma} - \frac{1}{\gamma}\frac{\frac{1-\beta}{\beta}e^{-(\rho+q)t}}{e^{-\gamma T(0)} + \frac{1-\beta}{\beta(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)} < 0,$$

5.4 Proof of Proposition 4

In (13), deriving with respect to D, we obtain

$$\frac{\partial(y(t;D))}{\partial D} = -y(t-D) < 0, \quad \frac{\partial(P(t;D))}{\partial D} = -y(t-D)e^{-\gamma D} < 0.$$

Table 1: Pollution equation without taking account of share of used goods

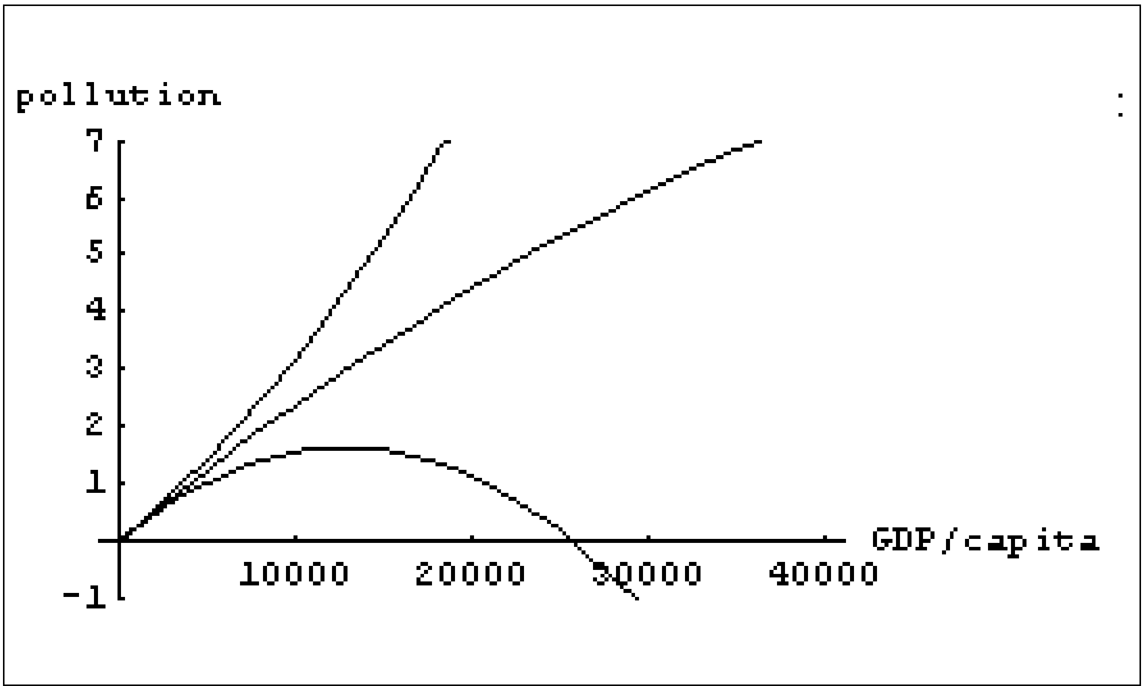
Dependent variable: CO_2/capita

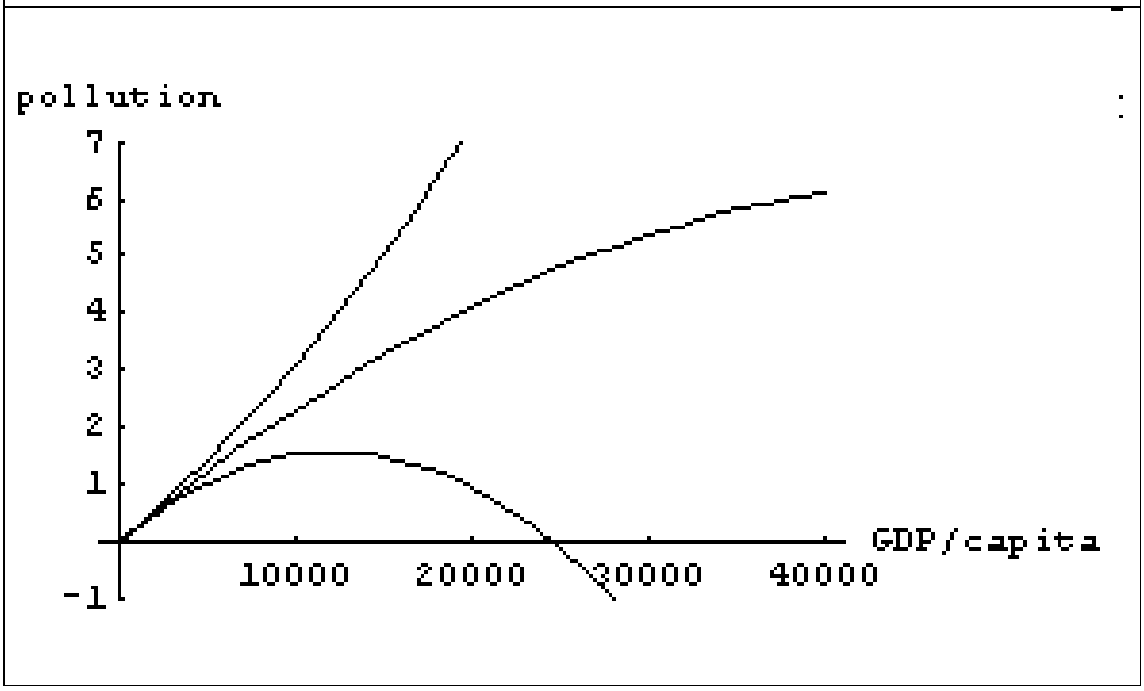
	(1)	(2)	(3)	(4)
GDP/capita	*0.000****	*0.000****	*0.000****	*0.000****
	(0.000)	*(0.000)*	*(0.000)*	*(0.000)*
$(GDP/capita)^2$		*-0.000****		*-0.000****
		(0.000)		*(0.000)*
Time dummies	*No*	*No*	*Yes*	*Yes*
Regional dummies	*No*	*No*	*Yes*	*Yes*
Observations	*664*	*664*	*664*	*664*
R-squared	*0.34*	*0.36*	*0.39*	*0.40*

Table 2: Pollution equation, taking account of share of used goods

Dependent variable: CO_2/capita

	(1)	(2)	(3)	(4)
Share used goods	-0.331**	0.033	-0.269*	0.088
	(0.146)	(0.196)	(0.144)	(0.193)
GDP/capita	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)
GDP/capita*Share	0.000***	-0.000	0.000***	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)
$(GDP/capita)^2$		-0.000***		-0.000***
		(0.000)		(0.000)
$(GDP/capita)^2$*Share		0.000**		0.000**
		(0.000)		(0.000)
Time dummies	No	No	Yes	Yes
Regional dummies	No	No	Yes	Yes
Observations	664	664	664	664
R-squared	0.35	0.37	0.39	0.41





N.B. : Coefficients α , θ_0, β_0, δ and λ have been normalized to zero so that all curves cross the origin. The coefficient γ_1 has been set to zero given in columns 2 and 4 of Table 2, it turned out to be statistically insignificant.